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Assessment of the Coordination Ability of Sustainable Social-Ecological Systems Development Based on a Set Pair Analysis: A Case Study in Yanchi County, China

Ya Wang [1,3] and Lihua Zhou [1,2,*]

1 Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; wy_2005@yeah.net
2 Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China
3 University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: lhzhou@lzb.ac.cn; Tel.: +86-10-5935-8704

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Abstract: Sandy desertification is one of the most severe ecological problems in the world. Essentially, it is land degradation caused by discordance in the Social-Ecological Systems (SES). The ability to coordinate SES is a principal characteristic of regional sustainable development and a key factor in desertification control. This paper directly and comprehensively evaluates the ability to coordinate SES in the desertification reversal process. Assessment indicators and standards for SES have been established using statistical data and materials from government agencies. We applied a coordinated development model based on Identical-Discrepancy-Contrary (IDC) situational ranking of a Set Pair Analysis (SPA) to analyze the change in Yanchi County's coordination ability since it implemented the grazing prohibition policy. The results indicated that Yanchi County was basically in the secondary grade of the national sustainable development level, and the subsystems' development trend was relatively stable. Coordinate ability increased from 0.686 in 2003 to 0.957 in 2014 and experienced "weak coordination to basic coordination to high coordination" development processes. We concluded that drought, the grazing prohibition dilemma and the ecological footprint were key factors impeding the coordination of SES development in this area. These findings should provide information about desertification control and ecological policy implementation to guarantee sustainable rehabilitation.

Keywords: social-ecological systems; sustainable development; coordination ability; set pair analysis; Yanchi County

1. Introduction

In recent years, with the gradual, in-depth study of the effect of global changes and the sharply increasing influence and pressure on the ecological environment caused by socioeconomic development and the irrational use of land resources, assessment of the sustainability of Social-Ecological Systems (SES) has become the focus of widespread concern for policy-makers, businesses managers, researchers and individuals. A social-ecological system is a compound system emerging from interactions between ecological and social systems [1–4]. This system contains the biology-geology-physics unit and its associated social roles and systems [5]. More generally, sustainability refers to a pattern or state that will continue in the time dimension, reflecting the endurance of systems and processes. When the concept expands to the geospatial dimension, sustainability is a judgment of long-term rationality in the development process for a country or region. For the SES, sustainability is the capacity to create, test and maintain adaptive capability, maintained by relationships that can be interpreted as a nested set of adaptive cycles arranged as a dynamic hierarchy in the panarchy of space and time [6]. Holling (2001) [7] integrates the concept of social-ecological systems and sustainability as sustainable development based on the adaptive cycles theory. He further clarifies the meaning of sustainable development through the panarchy model. The organizing principle for sustainability is sustainable development, which was viewed as a behavioral vector in the complex nature-society-economy system [8]. Sustainable development is a strategic process that can reflect the continuous, coordinated and equitable development of each element of an internal SES in the time and space dimension between intra-generational bodies and inter-generational bodies [9]. The ability to coordinate SES is a principal characteristic and original power of sustainable development. The ability to coordinate sustainable SES development depends on the relationship between its subsystems and elements and their associated structure and status [10]. Evaluating the coordination ability of SES for regional sustainable development is an important foundation and core concept [11]. The evaluation process is essentially a fuzzy analysis of the certainty and uncertainty characteristics of the SES [12]. The set pair analysis (SPA) method is a powerful tool for evaluating fuzzy information; its reliability and operability is better than those of other methods, and it can not only accurately analyze the complex, fuzzy and uncertainty problems of a SES, but also objectively reflect the subsystems' development trends and coordination between their internal elements. By judging the Set Pair Potential (SPP) of each SES subsystem and using a growth curve function to calculate the coordination ability of sustainable SES development, we can address the following issues using the traditional evaluation model: high correlation between indexes, a non-objective index weight and the results of linear mapping.

Sandy desertification is one of the most severe ecological and environmental problems in the world. It threatens over 100 countries, 3.6 billion km^2 of arable land and pastures and the survival and development of 1.2 billion people. The SES method is a new way of thinking in the ecological system analysis [13]. Sandy desertification is a product of the comprehensive influence between natural factors and human factors. It is a typical social-ecological system management issue. Essentially, sandy degradation is caused by internal dissonance in an SES. The problem of land desertification in Northern China is grim, with 40.50% of the land in the agro-pastoral zone having been desertified [14]. Yanchi County is a good research area because it is topographically and climatically a typical transitional zone with typical, vegetation and agriculture-animal husbandry production. Additionally, since the recent implementation of a series of ecological protection policies, such as the "grain for green project", "a grazing prohibition policy" and the "grassland ecological compensation award policy", desertification has shown a clear trend of reversal in this pastoral transitional zone [15–18], and the desertification area has been reduced at a rate of approximately 1280 $km^2 \cdot a^{-1}$ [19]. Indeed, Yanchi County has shown the most significant desertification reversal.

This study used typical representative and accessible data to select a typical area in which desertification has been reversed (Yanchi County) as a study area where human activity was clearly important, natural and human activities were highly associated and a large difference in desertification was observed. The connection number and set pair potential of the SPA method was used to grade and potentially analyze the ability of sustainable SES development in this county. According to the subsystem's SPP ranking to filter the data for the evaluation model of the coordination ability, assessment of the coordination ability of SES during the implementation of the grazing prohibition policy was conducted. The grazing prohibition policy served as a starting point to explore the reasons for changes in the coordination curve during different stages of the grazing prohibition policy. Our analysis provided scientific evidence for a temporal and spatial comparison and indicated future trends for sustainable development in this SES. Finally, our results will help support future management and regulation by addressing the desertification problem in a pastoral transitional zone, prompting the coordination of regional, ecological and economic development and the construction of an eco-friendly society.

2. Study Area

Yanchi County lies in the middle north of China, in the eastern part of the Ningxia Hui Autonomous Region (37°04′ N–38°10′ N, 106°30′ E–107°41′ E) [20]. It is bordered by the provinces of Gansu, Shaanxi, Ningxia and Inner Mongolia (Figure 1). The Mu Us Desert and the Loess Plateau are in the north and south of Yanchi County, respectively. Geographically, this area is topographically and climatically a typical transitional zone with typical vegetation and agricultural production. The area has a temperate continental climate, is highly susceptible to drought and is very windy and dusty. Yanchi County has a total area of 8.67 × 10^3 km^2 and contains 101 villages. The population density is 20.20 persons/km^2, which is higher than the United Nations mandate of 2014 for the critical population density of semi-arid areas (20 persons/km^2). The rural population is 13.91 × 10^4 and accounts for 81.08% of the total population. Between 2000 and 2013, the county's urban area expanded from 2.25 km^2–12.5 km^2 and green coverage increased from 6.85% in 2003 to 41.05% (nearly a six-fold increase). In 2003, the urbanization rate was 37.36%, and the urban/rural income gap was 3.23:1.

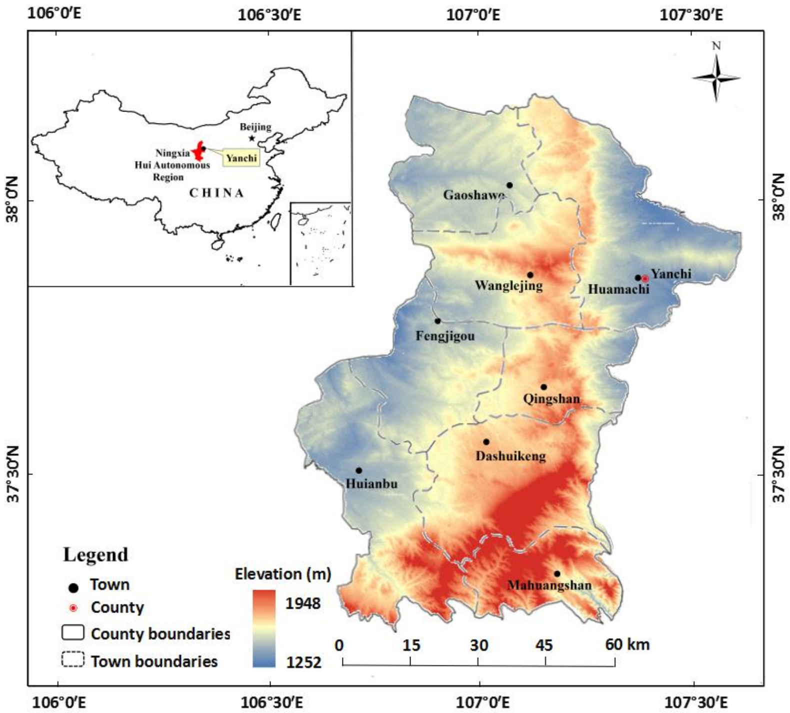

Figure 1. Location and administrative divisions of Yanchi County.

Yanchi County is known as the Chinese hometown of Tan sheep and licorice and is a typical agricultural and livestock-production area. The total area sown for crops is 8.28 × 10^4 ha, and the crops principally consist of maize, grass, buckwheat and potatoes. Yanchi County annually slaughters 7.57 × 10^5 sheep; the gross output value of animal husbandry is 6.11 × 10^8 Yuan (approximately 1.01 × 10^8 US$ at the 6.0712 US$-¥ exchange rate on 17 January 2014), accounting for 49.95% of total agricultural production and 10.65% of gross regional production in 2014. The total retail sales of consumer goods is 1.07 × 10^5 Yuan (approximately 1.76 × 10^4 US$ at the 6.0712 US$-¥ exchange rate on 17 January 2014); the consumption gap between urban and rural residents is 1.78:1; and the Engel coefficient (the proportion of total food expense to total personal consumption expense) of rural households is 1.81-times that of urban residents.

Ecosystems provide a series of services that improve human well-being, many of which are of fundamental importance to human society [21]. Assessing the value of ecosystem services in monetary units [22] is an important approach to reflect the impact of and change in the regional environment when natural and human factors (climate change, human activities and policy control) interfere with the ecosystem. The ecological environment of Yanchi County has gradually improved since November 2002, when the government implemented an ecological protection policy that requires the comprehensive fencing of grazing grassland. The ecological service value experienced an upward trend that increased from 4.15 $\times$ 10^9 Yuan in 2000 to 4.41 $\times$ 10^9 Yuan in 2010 [23]. At the same time, the trend of desertification reversal in this area was very clear, with the desert area decreasing from 3014 km^2 in 2000 [24] to 494.40 km^2 in 2010 [23]. The ratio of the vegetation coverage area (<10%), the soil organic matter content (<0.25%) and the per square meter of biomass fresh weight (<400 g), which indicated very severe desertification, decreased from 10.18% in 1999 to 6.51% in 2010 [25]. The unit output value of the land rose from 2.93 $\times$ 10^4 Yuan/ha in 2000 to 23.76 $\times$ 10^4 Yuan/ha in 2008. The grass yield of per hectare meadow increased from 701 kg/ha in 2000 to 1980 kg/ha in 2011.

3. Methods and Data

3.1. Principle and Application of Set Pair Analysis

Set Pair Analysis (SPA) is an uncertainty analysis theory based on a combination of dialectical thinking and mathematical methods and was proposed by Zhao Keqin (1992) [26]. SPA overcomes the limitations of the classical set and fuzzy sets methods. Additionally, it avoids the shortcomings that have characterized research into the uncertainty problem from the certainty perspective in the past and facilitates quantitative descriptions of quantitative and qualitative conversion processes based on mathematical expressions. SPA can better express the global and local structure of a relationship than, for example, contact coefficients, membership degree and gray correlation. Furthermore, it avoids some issues associated with the fuzzy comprehensive evaluation and gray clustering methods, in which the results of the calculations are discrete, the transitions between each level are difficult to describe and the accuracy of the evaluation is low. This method has been widely applied in the artificial intelligence, hydrology, information and management, resources and environment, as well as the social and economic fields. This wide application is because SPA involves a relatively simple calculation process, and its results more closely approximate the actual situation than those of the fuzzy comprehensive evaluation, projection pursuit and attribute recognition methods.

The basis and key to SPA is building the set pair and computing the connection degree. Its core procedure consists of combining two sets A and B as the set pair $H(A, B)$ to form a certain-uncertain system under defined circumstances and then analyzing features of H from three perspectives (Identical-Discrepancy-Contrary (IDC)) based on the formula for the connection degree [27]; its internal relationship is shown in Figure 2a. We defined the IDC three-element connection degree $\mu(A, B)$ as follows:

$$\mu(A,B) = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj \quad (1)$$

where $\mu(A, B)$ is the three-element connection degree of the set pair $H(A, B)$, $\mu \in [-1, 1]$; N is the sum of the features; S is the co-owner feature number of the two sets; and P is the opposition feature number of H; $F = N\text{-}S\text{-}P$ represent numbers that are neither the same nor opposite. The components a, b, c are called the identical component, the discrepancy component and the contrary component of the connection degree under a given background, respectively, and satisfy the equation $a + b + c = 1$; i is the difference uncertainty coefficient, $I \in [-1, 1]$. j is the opposition coefficient, which is generally taken as -1.

The four-element connection degree is an expanded form of the IDC of the three-element connection degree in discrepancy portions (i). Its internal relationship is shown in Figure 2b, and its general form is as follows:

$$\mu(A,B) = \frac{S}{N} + \frac{F_1}{N}i_1 + \frac{F_2}{N}i_2 + \frac{P}{N}j = a + bi + cj + dk \quad (2)$$

where $\mu(A, B)$ is the four-element connection degree of the set pair $H(A, B)$, $\mu \in [-1, 1]$; N is the sum of the features; S is the co-owner feature number of the two sets; P is the opposition feature number of H; and F_1 and F_2 represent numbers that are neither the same nor opposite. The components a, b, c, d are called the identical component, the identical-discrepancy component, the discrepancy-contrary component and the contrary component of the connection number under a given background, respectively, and their values are all in the range [0, 1] and satisfy the equation $a + b + c + d = 1$; i and j are the difference uncertainty coefficients, $I \in [0, 1]$, $j \in [-1, 0]$; and k is the opposition coefficient, which is generally taken as −1.

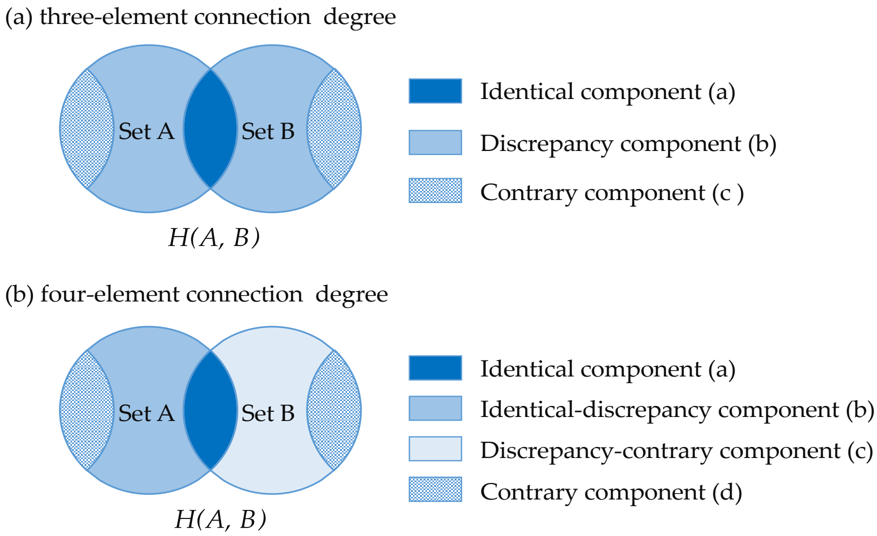

Figure 2. The schematic diagram of internal relationship between each component of the Set Pair Analysis (SPA) connection degree.

3.2. Construction of an Index System for Sustainable SES Development

SES is a complicated adaptive system that closely links humans and natural systems [28]. It has two core elements: the social and ecological. SES is the basic functional unit of the human wisdom circle [29], and its characteristics are historical dependence, the threshold effect, unpredictability, self-organization, non-linearity and multiple-stability when perturbed by internal and external driving factors [28,30–33]. This paper will evaluate sustainable development with respect to the social subsystem, the economic subsystem and the ecological subsystem according to the SES structure division research of Ma Shijun (1993) [34]. It considers not only the features of SES structural elements at the system level, but also the requirements for sustainable development. Based on the availability and feasibility of the indicator considered and a variety of evaluation index systems for sustainable development, we selected higher frequency applications and strong representative indicators for description and analysis (Table 1). The social development indicators S1–S6 separately consider overall development, income, housing, medical care and employment to reflect the current state of the system. The economic development indicators G1–G6 characterize the structure and average level of economic development, people's consumption structure and income levels and energy consumption. The environmental indicators E1–E6 reflect the possession of resources, ecological change, environmental consumption and solid waste disposal. Considering each of these indicators independently and roughly describes the entire social-economic-ecological system, providing a foundation for estimating the accuracy of the evaluation. To meet the usability, operability and simple practicality criteria for index selection and the authenticity and comparability of the results, we used mean, unit mean and percentage data in addition to environmental quality indicators.

Table 1. The assessment indicators and grading standards of sustainable development. SES, Social-Ecological System.

Target Layer	System Layer	Index Layer	Assessment Standard			
			First Standard	Second Standard	Third Standard	Fourth Standard
Sustainable SES development	Social system	S1 Urbanization rate (%) +	<26	26–60	60–80	>80
		S2 Net income per capita (¥·person^{-1}) +	<2478	2478–8000	8000–10,000	>10,000
		S3 Urban residents disposable income (¥·person^{-1}) +	<4900	4900–25,000	25,000–30,000	>30,000
		S4 Urban residents per capita housing floor space now (m^2·person^{-1}) +	<13	13–25	25–30	>30
		S5 Medical beds one in 1000 (bed) +	<2	2–10	10–20	>20
		S6 Registered unemployment rate in town (%) −	>8	4.6–8	2–4.6	<2
	Economic system	G1 Per capita GDP (¥·person^{-1}) +	<7592	7592–30,000	30,000–80,000	>80,000
		G2 Tertiary industries accounting for the proportion of GDP (%) +	<32	32–60	60–80	>80
		G3 Urban units staff average wage (¥·person^{-1}) +	<7780	7780–50,000	50,000–60,000	>60,000
		G4 Engel's coefficient of rural family (%) −	>43	40–43	30–40	<30
		G5 Engel's coefficient of urban family (%) −	>43	40–43	30–40	<30
		G6 Energy consumption per 10,000 ¥ GDP (tce) −	>2	0.6–2	0.4–0.6	<0.4
	Ecological system	E1 Water resources per capita (%) +	<31	31–1700	1700–3000	3000
		E2 Vegetation coverage rate (%) +	<10	10–35	35–60	>60
		E3 Climate Evaporation Index (%) −	>4	1.5–4	1–1.5	<1
		E4 Desertification land proportion (%) −	>40	25–40	10–25	<10
		E5 Per capita ecological footprint (gha·person^{-1}) −	>4	2.6–4	1.5–2.6	<1.5
		E6 Comprehensive utilization rate of industrial solid waste (%) +	<40	40–60	60–80	>80

+: representative the benefit index, it refers to the indicators that its value is the bigger the better; −: representative the cost index, it refers to the indicators that its value is the smaller the better. S4: $H_P = \left(\sum H_T/N_R\right)/S$, where H_P is the indicator of urban residents per capita housing floor space, H_T is a household's total housing area, N_R is the number of household members in the registered residence, S is the number of sampling. S5: $M_B = B_T/1000$, where M_B is the medical beds one in one thousand and B_T is the total number of beds. E3: This represents the degree of climate dryness. $CEI = E/P$, where CEI is the climate evaporation index, E is the evaporation and P is the precipitation.

3.3. Evaluation Criteria for Sustainable Development

Because the screening indicators had horizontal and vertical comparability, four evaluation criteria were selected as the first, second, third and fourth standards, and the third standard was designated as the main line of the entire standard system. Based on national environmental standards, the Twelfth Five-year Development Plan and an environmental protection plan, we drafted Yanchi County's individual indicator evaluation standards in the context of national sustainable development. At the same time, we referred to the status values of developed countries and more developed domestic regions (for example, the cities of Beijing, Shanghai and Guangzhou) and reviewed Tan Feifei's research (2014) [12], which classified the evaluation standards of the corresponding sustainable development evaluation indicators in the JingJinJi region. For the social indicators, S1 conformed to the social development goals of the national Twelfth Five-year Plan and the current levels of the United Kingdom and the United States. S2–S6 were in accordance with the status values of more developed domestic regions (for example, the cities of Beijing, Shanghai and Guangzhou). The economic indicators refer to the Twelfth Five-year Plan. For the ecological indicators, E1 was referenced to the mild water shortage index according to the United Nations Water Organization, E2–E4 to the classification standards of arid and semi-arid areas and E5 to China's ecological footprint data from 2003 and the global value in 2008. Finally, grades were also assigned according to the State Ministry of the Comprehensive Utilization of Industrial Solid Waste's Twelfth Five-year Plan. The specific standards' results are listed in Table 1.

3.4. Construction of the Evaluation Model of Coordination Ability for an SES

To assess the coordination ability of sustainable regional SES development via SPA, the first step is to designate each index value in the evaluation sample as set A_i (= 1, 2, ..., N; N is the index number), and to establish the evaluation criteria of the corresponding index as set B_s ($s = i$ = 1, 2, ..., K; K is the standard number). Second, each evaluation criterion and index value of the evaluation samples is quantitatively determined; the set pair $H(A_i, B_s)$ is constructed; and the symbol elements of A_i and one standard B_s are compared. Finally, the number of the same S values, the difference F_1, the difference of 2 F_2, and the difference of K−2 P are calculated. The numerical calculation of the contact components a, b, c and d for the various evaluation criteria is shown in Table 2.

Table 2. Calculation of the contact components a, b, c and d of the four-element connection degree.

Assessment Standard	*a*	*b*	*c*	*d*
First standard	*N1/N*	*N2/N*	*N3/N*	*N4/N*
Second standard	*N2/N*	*(N1+N3)/N*	*N4/N*	*0*
Third standard	*N3/N*	*(N2+N4)/N*	*N1/N*	*0*
Fourth standard	*N4/N*	*N3/N*	*N2/N*	*N1/N*

N is the total number of indicators; *N1* is the number of indicators in line with the first standard; *N2* is the number of indicators in line with the second standard; *N3* is the number of indicators in line with the third standard; and *N4* is the number of indicators in line with the fourth standard.

The connection number ($\mu_{A\text{-}B}$) is a comprehensive quantitative indicator of connection degree, and it characterized the comprehensive relationship degree between set A and set B. When the quantitative value of $\mu_{A\text{-}B}$ is more close to 1, the two sets are more inclined to be identical in a particular attribute. Conversely, when the quantitative value of $\mu_{A\text{-}B}$ is closer to −1, the two sets are more inclined to be contrary in a particular attribute. When the quantitative value of $\mu_{\boldsymbol{A}\text{-}\boldsymbol{B}}$ is closer to 0, the two sets are more inclined to have a discrepancy (neither the same nor opposite) in a particular attribute [35]. We can use the uniform value method (Equation (3)) to calculate the coefficients of the differences' uncertainty component I_k. When $\mu(A, B)$ is the four-element connection degree, the discrepancy portions (i) of three-element connection degree will decompose into i and j; $i \in [0, 1]$ represent the differences and uncertainty degree of the identical-discrepancy component; $j \in [-1, 0]$ represent the differences and uncertainty degree of the discrepancy-contrary component.

$$I_k = 1 - \frac{2k}{K-1}, \mathrm{k} = 1, 2, \ldots, K-2 \quad (3)$$

where I_k is the differences' uncertainty component; k is the assessment standard grade; and K is the grade number.

SPP is an adjoint function of the connection number. It indicates the situation information of the contact number in terms of the size of the contact component and its relationship, thus reflecting the developmental states and dynamic evolutionary trends of the two sets [36]. Three types of SPP can be considered: the set pair identical potential, the equalization potential and the contrary potential. The set that shows the same trend in the IDC connection is the set pair identical potential; the set that exhibits the contrary trend is the contrary potential; and the set that shows a balance between the identical trend and the contrary trend is the equalization potential. The grade and sorting of SPPs of the four-element connection number are shown in Table 3. Each set that has a corresponding situation degree can be expressed in the range of [0.1, 1] [36].

Table 3. The four-element connection number of the rank and value of the set pair potential.

Set Pair Potential	Situation Level	Rank	Size and Relationship of a, b, c, d	Situation Value
Identical Potential (IP, 1–19)	Quasi-Identical Potential (QIP, 1–2)	1	a > d, a > b, b > c, c > d	1.0
		2	a > d, a > b, b > c, c = d	
	Strong Identical Potential (SIP, 3–9)	3	a > d, a > b, b > c, c < d	0.9
		4	a > d, a > b, b = c, c > d	
		5	a > d, a > b, b = c, c = d	
		6	a > d, a > b, b = c, c < d	
		7	a > d, a > b, b < c, c > d	
		8	a > d, a > b, b < c, c = d	
		9	a > d, a > b, b < c, c < d	
	Weak Identical Potential (WIP, 10–14)	10	a > d, a = b, b > c, c > d	0.8
		11	a > d, a = b, b > c, c = d	
		12	a > d, a = b, b > c, c < d	
		13	a > d, a = b, b = c, c > d	
		14	a > d, a = b, b < c, c > d	
	Micro Identical Potential (MIP, 15–19)	15	a > d, a < b, b > c, c > d	0.7
		16	a > d, a < b, b > c, c = d	
		17	a > d, a < b, b > c, c < d	
		18	a > d, a < b, b = c, c > d	
		19	a > d, a < b, b < c, c > d	
Equalization Potential (EP, 20–30)	Strong Equalization Potential (SEP, 20–22)	20	a = d, a > b, b = c, c > d	0.6
		21	a = d, a > b, b < c, c = d	
		22	a = d, a > b, b < c, c < d	
	Weak Equalization Potential (WEP, 23–26)	23	a = d, a = b, b > c, c < d	0.5
		24	a = d, a = b, b = c, c = d	
		25	a = d, a = b, b < c, c > d	
		26	a = d, a < b, b > c, c > d	
	Micro Equalization Potential (MEP, 27–30)	27	a = d, a < b, b > c, c = d	0.4
		28	a = d, a < b, b > c, c < d	
		29	a = d, a < b, b = c, c > d	
		30	a = d, a < b, b < c, c > d	

Table 3. *Cont.*

Set Pair Potential	Situation Level	Rank	Size and Relationship of a, b, c, d	Situation Value
Contrary Potential (CP, 31–49)	Micro Contrary Potential (MCP, 31–34)	31	a < d, a > b, b > c, c < d	0.3
		32	a < d, a > b, b = c, c < d	
		33	a < d, a > b, b < c, c > d	
		34	a < d, a > b, b < c, c < d	
	Weak Contrary Potential (WCP, 35–40)	35	a < d, a = b, b > c, c > d	0.2
		36	a < d, a = b, b = c, c > d	
		37	a < d, a = b, b = c, c < d	
		38	a < d, a = b, b < c, c > d	
		39	a < d, a = b, b < c, c = d	
		40	a < d, a = b, b < c, c < d	
	Strong Contrary Potential (SCP, 41–49)	41	a < d, a < b, b > c, c > d	0.1
		42	a < d, a < b, b > c, c = d	
		43	a < d, a < b, b > c, c < d	
		44	a < d, a < b, b = c, c > d	
		45	a < d, a < b, b = c, c = d	
		46	a < d, a < b, b = c, c < d	
		47	a < d, a < b, b < c, c > d	
		48	a < d, a < b, b < c, c = d	
		49	a < d, a < b, b > c, c < d	

The Coordination Ability Index (CAI) is a quantitative indicator that reflects the degree and state of harmony between the systems and their internal elements in the development process. This indicator embodies the system development trend from disorder to order. The size of the contact components of each indicator determines the situation degree values d_s, d_g and k that are used to describe and calculate the relationships between SES and CAI by using the growth curve function (Equation (4)).

$$CAI = \frac{1}{1 + ke^{-d_s \cdot d_g}} \quad (4)$$

where d_s is the social progress situation degree, d_g is the economic development situation degree and k is the ecological environment situation degree of dysfunction.

According to Equation (4), when the social and economic situation degrees are small ($d_s = d_g = 0.1$), but the ecological environment damage situation degree is large ($k = 1$), the coordinated development index of the three degrees is $I_{min} = 0.50$. Additionally, when the social and economic situation degrees are large ($d_s = d_g = 1$) and the ecological environment damage situation degree is small ($k = 0.1$), the coordinated development index of the three degrees is $I_{max} = 0.97$; when $d_s = d_g = k = 0.5$, $I = 0.72$. Thus, we can define the values [0.50, 0.60] as inharmonious sustainable SES development, [0.60, 0.72] as weak coordination, [0.72, 0.85] as basic coordination and [0.85, 0.97] as high coordination [37].

3.5. Data Sources

The socioeconomic data are taken from the "Ningxia Statistical Yearbook" (2003–2015) [38] and the "National Economic and Social Development Statistics Bulletin of Yanchi County" (2008–2014) [39]. The proportion of sand, the vegetation coverage and the grass yield per hectare of meadow data are statistical data from the Department of Animal Husbandry and the Land Office from 2003–2014. The water resources per capita index (2007–2014) was provided by the Yanchi County Water Supply Corporation. The per capita ecological footprint data were obtained from the doctoral dissertation of Ma Mingde [40].

4. Results and Analysis

The grazing prohibition policy played a very important role in SES development in Yanchi County based on livestock production. This policy both promoted changes in farmers' traditional animal husbandry production and livelihood strategies and affected local labor allocation and social and economic industrial restructuring. Therefore, this paper used the grazing prohibition policy as a starting point to analyze the variation characteristics of the coordination ability of sustainable SES development in Yanchi County during different periods in which grazing prohibition varied. We selected key time points are based on the implementation of the grazing prohibition policy. Yanchi County implemented the grazing prohibition policy in November 2002, to match up the grazing prohibition policy and respond to the national arrangement to begin full implementation of the grassland ecological complement award policy in 2011. Thus, this period was divided into the early stage (2003–2005), the middle stage (2006–2010) and the present stage of grazing prohibition (2011–2014).

4.1. Grading of Sustainable SES Development Based on the Connection Degree

The value $I = 1/3$, $J = -1/3$ was calculated by using the uniform values method, and the connection numbers for each set were obtained via Equation (2) with $K = -1$ (Table 4). Depending on the maximum connection number judgment rule, the sustainable development grade evaluation for each dimension and year can be obtained for the SES. The results showed the following: (1) In Yanchi County, the sustainable SES development grade was determined in the second standard; the economic system was in the second standard, except in 2014; the ecological system was in the second or third standard, except for 2014, when the fourth standard was achieved, exceeding the grades of the social and economic systems in the early and middle stages of grazing prohibition. (2) For the social system, the level of sustainable development was minimized in 2006 (of the six indicators characterizing the sustainable development of the social system, no indicators met the fourth standard, and thus, the identical value was zero; in contrast, the contrary value reached a maximum at 0.4). In the remaining years, the connection number and identical value gradually increased to the third and fourth standards. However, sustainable development experienced a declining trend during the early stage of grazing prohibition, which subsequently increased. (3) Because of the global financial crisis in 2008, the economic system's connection numbers that satisfied the second, third and fourth standards declined yearly during 2008–2010, leading to a reduction in the sustainable development level of this system during the middle stage of grazing prohibition. After 2011, a decrease in the connection number in the first and second standards and an increase in the connection number and identical value in the third and fourth standards indicated that the sustainable development capacity of the economic system gradually improved during the present stage of grazing prohibition.

Table 4. The development and grades of the SES in Yanchi County from 2003–2014.

Year	Social System					Economic System					Ecological System				
	$\mu_{Ai\text{-}B1}$	$\mu_{Ai\text{-}B2}$	$\mu_{Ai\text{-}B3}$	$\mu_{Ai\text{-}B4}$	Grade	$\mu_{Ai\text{-}B1}$	$\mu_{Ai\text{-}B2}$	$\mu_{Ai\text{-}B3}$	$\mu_{Ai\text{-}B4}$	Grade	$\mu_{Ai\text{-}B1}$	$\mu_{Ai\text{-}B2}$	$\mu_{Ai\text{-}B3}$	$\mu_{Ai\text{-}B4}$	Grade
2003	0.22	0.44	0.22	−0.22	Second	0.33	0.47	0.07	−0.33	Second	0.33	0.47	0.07	−0.33	Second
2004	0.11	0.56	0.33	−0.11	Second	0.47	0.60	0.20	−0.22	Second	−0.07	0.33	0.47	0.07	Third
2005	0.22	0.67	0.44	−0.22	Second	0.47	0.60	0.20	−0.47	Second	−0.07	0.33	0.47	0.07	Third
2006	0.33	0.56	0.33	−0.33	Second	0.47	0.60	0.20	−0.47	Second	0.47	0.33	0.73	0.07	Third
2007	0.22	0.67	0.44	−0.22	Second	0.22	0.89	0.44	−0.22	Second	0.11	0.33	0.33	−0.11	Second/Third
2008	0.22	0.67	0.44	−0.22	Second	0.33	0.78	0.33	−0.33	Second	0.22	0.44	0.22	−0.22	Second
2009	0.11	0.78	0.56	−0.11	Second	0.33	0.78	0.33	−0.33	Second	0.11	0.33	0.11	−0.11	Second
2010	0.11	0.78	0.56	−0.11	Second	0.33	0.78	0.33	−0.33	Second	0.11	0.11	0.11	−0.11	First/Second/Third
2011	0.11	0.78	0.56	−0.11	Second	0.44	0.67	0.22	−0.44	Second	−0.11	0.33	0.33	0.11	Second/Third
2012	0.11	0.78	0.56	−0.11	Second	0.39	0.67	0.22	−0.44	Second	0.11	0.33	0.11	−0.11	Second
2013	0.00	0.67	0.44	0.00	Second	0.22	0.67	0.22	0.33	Second	−0.11	0.11	0.11	0.44	Fourth
2014	0.00	0.67	0.44	0.00	Second	0.00	0.44	0.44	0.00	Second/Third	−0.07	0.33	0.20	0.07	Second

4.2. Situation Sorting and Dynamic Evolution of the SES Based on the SPP

For the first standard set pair, the situation trends of the sustainable development of the social and ecological subsystems changed from "weak identical potential" to "strong identical potential" (Table 5). The set pair situation variation of the economic system was relatively stable, whereas that of the social system fluctuated widely, indicating that the identical development trend of the economic system was higher and had the same trend in the first standard. However, the contrary development trend of the ecological system exhibited a higher standard. The set pair situation of the ecological system varied the most among the three subsystems: "weak identical potential-micro equalization potential-strong identical potential-micro contrary potential-strong contrary potential". Because the coordination model required the situation of ecological damage as a variable, the situation of the ecological system was set to be located in the first standard as the value representation to describe this variable.

For the second standard set pair, the set pair situation variation in the social, economic and ecological systems was relatively stable, shifting from "weak identical potential" to "strong identical potential" and indicating that Yanchi County's identical SES development level was higher in the second standard, consistent with the results of the sustainable development level indicated by the connection degree. Therefore, the situation values of the social and economic systems in the second standard should be the representative indicator of the social and economic development situations in the growth curve function.

For the third standard set pair, the development situation of the social system was generally in micro identical potential, except during 2006, when it was in weak identical potential. The economic system moved from "weak equalization potential-micro identical potential-strong contrary potential-weak equalization potential-micro identical potential", spending eight years in the micro identical potential. The ecological system alternated from "weak equalization potential" to "micro identical potential". In summary, each system's identical set pair situation variation in the third standard was below the second standard, whereas the opposite trend in the economic system was notable.

For the fourth standard set pair, the sustainable development situation trend of each SES subsystem fluctuated greatly, but showed essentially the same trend: "contrary potential" to "identical potential" over time. The smallest fluctuations were noted in the economic system, including eight years of the strong contrary potential; thus, this system's sustainable development level had not reached the fourth standard. The ecological system's set pair situation fluctuated widely, changing from "micro contrary potential" to "strong identical potential" over time.

Table 5. The set pair trend and order of the SES in Yanchi County from 2003–2014.

Year	$H(A_i, B_1)$						$H(A_i, B_2)$						$H(A_i, B_3)$						$H(A_i, B_4)$					
	Social System (d_s)		Economic System (d_g)		Ecological System (K)		Social System (d_s)		Economic System (d_g)		Ecological System (K)		Social System (d_s)		Economic System (d_g)		Ecological System (K)		Social System (d_s)		Economic System (d_g)		Ecological System (K)	
	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level	Rank	Level
2003	11	WIP	12	WIP	12	WIP	15	MIP	10	WIP	10	WIP	15	MIP	26	WEP	26	WEP	39	WCP	33	MCP	33	MCP
2004	27	MEP	12	WIP	25	WEP	1	QIP	15	MIP	15	MIP	15	MIP	18	MIP	10	WIP	25	WEP	44	SCP	27	MEP
2005	15	MIP	12	WIP	25	WEP	11	WIP	15	MIP	15	MIP	15	MIP	18	MIP	10	WIP	47	SCP	48	SCP	27	MEP
2006	13	WIP	12	WIP	27	MEP	16	MIP	15	MIP	27	MEP	13	WIP	18	MIP	30	MEP	45	SCP	48	SCO	43	SCP
2007	15	MIP	26	WEP	7	SIP	11	WIP	1	QIP	15	MIP	15	MIP	16	MIP	10	WIP	47	SCP	30	MEP	43	SCP
2008	15	MIP	15	MIP	11	WIP	11	WIP	1	QIP	15	MIP	15	MIP	15	MIP	15	MIP	47	SCP	41	SCP	39	WCP
2009	26	MEP	15	MIP	23	WEP	2	QIP	1	QIP	13	WIP	16	MIP	15	MIP	26	WEP	30	MEP	41	SCP	21	SEP
2010	26	MEP	15	MIP	9	SIP	2	QIP	1	QIP	26	WEP	16	MIP	15	MIP	15	MIP	30	MEP	41	SCP	31	MCP
2011	26	MEP	15	MIP	41	SCP	2	QIP	11	WIP	13	WIP	16	MIP	41	SCP	15	MIP	30	MEP	47	SCP	7	SIP
2012	26	MEP	15	MIP	23	WEP	2	QIP	11	WIP	13	WIP	16	MIP	41	SCP	26	WEP	30	MEP	47	SCP	21	SEP
2013	42	SCP	28	MEP	31	MCP	4	SIP	4	SIP	19	MIP	16	MIP	26	WEP	26	WEP	14	WIP	15	MIP	7	SIP
2014	42	SCP	28	MEP	41	SCP	4	SIP	4	SIP	7	SIP	16	MIP	15	MIP	26	WEP	14	WIP	29	MEP	7	SIP

4.3. Analysis of the SES Coordination Ability Based on the Growth Curve Index

The result of the set pair situation degree was obtained according to the requirements of the growth curve calculation; the IDC situation rank of set $H(A_i, B_2)$ was chosen as the situation value for the social and economic systems, and the IDC situation rank of set $H(A_i, B_1)$ was used as the environmental damage situation value for the ecological system. Next, the coordination ability of sustainable SES development was evaluated (Figure 3). The results showed the following: the SES coordination ability increased from 0.686 in 2003 to 0.957 in 2014, corresponding to the period during which Yanchi County implemented the grazing prohibition policy; this index curve showed a downwards trend in 2005, 2007 and 2010 and moved from "weak coordination to basic coordination to high coordination".

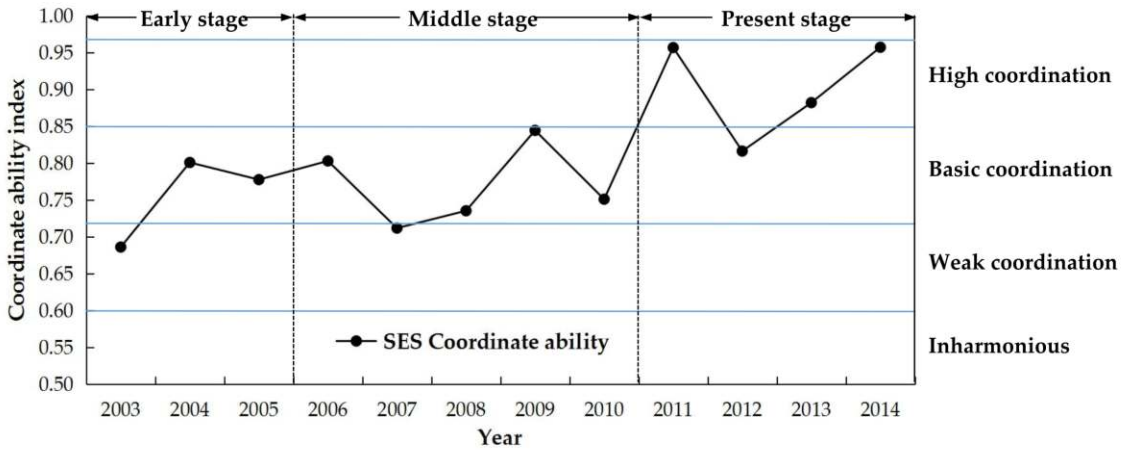

Figure 3. Change of the SES coordination ability index in Yanchi County from 2003–2014.

Regarding the different stages of the grazing prohibition policy, Yanchi County's coordination ability was basically maintained at a high coordination level during the present stage of grazing prohibition, increasing by 39.49% from 2003–2014. The status of the social, economic and ecological subsystems improved considerably with respect to the early stage of the grazing prohibition. The ecological damage situation trend showed the most obvious and critical decrease, suggesting that the national environmental protection policy substantially enhanced regional SES coordination ability. The result of an Ordinary Least Squares (OLS) regression analysis showed that the SES coordination ability was well fitted by subsystems development ($R^2 = 0.991$, observations number = 12, probability < 0.001). The significance values of the social, economic and ecological systems were 0.0017, 0.0002 and <0.0001. When the sustainable development levels of the social and economic systems were increased by one unit, the SES coordination abilities increased by 0.131 and 0.179, respectively. In contrast, when the ecosystem's value decreased by one unit, the SES coordination ability declined by 0.310. These results indicated that Yanchi County was an ecologically fragile area and that the underlying vulnerability of the ecological environment was the key obstacle restricting sustainable and coordinated development in this region.

4.4. Analysis of the Variation of the SES Coordination Ability in the Different Stages of the Grazing Prohibition Policy

The grazing prohibition policy effectively balanced the grassland yield and livestock demand, gradually reducing sandy areas and increasing vegetation coverage, indicating a reversal of desertification with consequent ecosystem rehabilitation. The ecological damage situation trend decreased from 0.8 down to 0.5, and the SES coordination ability followed an inverted "V" pattern, gradually shifting from "weak coordination" to "basic coordination" during the early stages (2003–2005). In 2005, the coordination ability between the systems dropped to 0.778 because of drought, although the value still indicated a "basic coordination" level.

In the middle stage of the grazing prohibition (2006–2010), the SES coordination ability first decreased and then increased, resulting in a "U"-shaped trend on the "basic coordination" level. The grazing prohibition policy changed households' traditional land use patterns; the households could not adapt to the changing production factors and labor investment and the objective fact of a short-term income decline. Field research by Chai Haofang et al. [41] indicated that the implementation of the grazing prohibition policy in Yanchi County gradually weakened after the initial stage from the top-down. However, a dilemma arose from 2006–2010. The regulatory costs for the high pastures and the contradictory official performance assessments caused the local government to adopt elasticized strategies when executing the policy. Farmers secretly grazing at night had been an open secret and even gained semi-legal status. The number of breeding sheep increased yearly, thereby increasing the pressure on the ecosystem's resources. As a result, SES coordination capacity declined from "basic coordination" to "weak coordination". Rechecking the systems' set pair process indicated that six indicators characterized the sustainable development of the Yanchi County economic system, whereas only five comprised the second standard in 2007, decreasing to four from 2008–2010. The original data indicated that the indicator of per capita Gross Domestic Product (GDP) increased from 6102 in 2005 to 17,913 in 2010, corresponding to a mean of 24.26% growth each year. The Engel coefficient of rural households declined from 49.76% in 2003 to 42.84% in 2010. This indicator remained at 42% during the present stage, suggesting that economic development effectively increased farmers' income. Furthermore, the proportion of personal consumption expenditures for the purchase of food decreased, whereas the proportion of investment in education and production increased. Enhancing the sustainable development of the economic system can effectively promote the diversification of farmers' livelihoods and a transformation from traditional grazing to feed or scale farming. Although the grazing prohibition dilemma decreased the sustainable development of the ecosystem, by increasing the economic system's development capacity, local SES coordination ability steadily rose to 0.845 in 2009. Yanchi County was influenced by climatic factors in 2010 (drought and an increased number of windy days), reducing the sustainable development of the ecological system and the coordination ability between systems.

During the present stage of grazing prohibition (2011–2014), Yanchi County's SES coordination ability increased yearly and changed from "basic coordination" to "high coordination" because of a notable improvement in the social subsystem's development capacity and a notable decrease in environmental damage in the ecological system; the latter had an especially large impact. Every year since 2009, four of the six indicators of Yanchi County's social development representation have been accorded with the second standard. An improvement in the state of social development could contribute to reducing the environmental impact and effectively enhance the coordination ability by mobilizing social resources to mitigate and adapt to environmental impacts. The original data indicated that the urbanization level, the income levels of urban and rural residents and the per capita housing floor space of urban residents had notably improved by the present stage. The grazing prohibition policy dilemma was broken by government adjustment of the management of mandatory regulations to incentivize ecological conservation. Since 2011, Yanchi County has implemented a grassland ecological compensation award policy. This policy protects grassland ecology; guarantees the supply of characteristic animal production, such as beef and mutton; promotes farmers' and herdsmen's income growth; and effectively alleviates the contradiction between the policy's long-term ecological benefits and short-term economic benefits to the herdsman. Since enacting this policy, grassland ecology and vegetation coverage have recovered. Whereas the per capita ecological footprint increased rapidly by 42.69% compared to the previous year, coordination ability dropped to 0.817 in 2012.

5. Discussion

5.1. Advantages and Applicability of the Method

An SES is a complex system with countless certain and uncertain elements. Additionally, sustainable development is multi-disciplinary, and thus, an objective scientific evaluation of sustainable SES development is problematic for researchers. This article applied the SPA method to assess sustainable SES development in a pastoral transitional zone. This method allowed us to identify and quantify the ambiguity and uncertainty of each subsystem and to take full account of the relevance and the differences between the values of indicators and the evaluation level to fully ascertain the development trend of each subsystem and the coordination between internal elements. The situation degree measuring the extents of social, economic and ecological development agrees with the physical theory of potential. The growth curve index describes the mutual relationships and the coordination capacity of each social-ecological subsystem according to the rules of development. In addition, this method is simple and highly adaptable, and its results are both intuitive and clear. There is room for improvement because the importance of different indicators varies and affects the evaluation results. In short, it is extremely important to assess the coordination ability using the SPA method to improve and enrich the quantitative evaluation of sustainable development.

5.2. Comparison and Discussion of Results

Results are based on the SPA method and demonstrate that the sustainable SES development of Yanchi County was maintained at the second grade of the national sustainable development level, and coordination ability increased yearly. Ma Mingde (2014) [42] has found that the degree of coordination of an agricultural economy and agro-ecosystems increased each year from 0.40 in 1990 to 0.87 in 2012. This finding shows that along with the development of Yanchi County's agricultural economy, the agricultural ecological environment improved [42]. Compared to Ma's results, we found that during 2003–2008, the coordination degree of the agricultural economy-agricultural ecosystem and regional SES coordination ability moved in opposite directions, whereas after 2009, the relationship changed to progress in the same direction. We believe that this divergence might be related to an external disturbance factor: the grazing prohibition policy. Many farmers cannot adapt to the impact on their traditional livelihood by the enforcement of the grazing prohibition policy, and they had to cope with the objective reality that their feed cost increased while their income declined. Farmers are rational agents: to maximize their economic benefits, they engaged in illegal grazing to reduce the economic losses caused by the grazing prohibition policy. Objectively, the implementation of the grazing policy reduced the impact of human activity on ecosystems and promoted coordinated SES development. However, the following three contradictions gradually accumulated. These contradictions are rooted in the imbalance between the agricultural body and ecological policy, short-term economic interests and long-term ecological interests, the agricultural economy and the agricultural ecosystem. Consequently, great instability emerged in the Yanchi County SES, and thus, Yanchi County's SES coordination ability declined and fluctuated widely from 2003–2008. The agricultural economy-agricultural ecosystem is a sector subsystem of a regional SES. Whether its internal elements are coordinated and trend in the same direction as the SES critical problem reflects a pastoral transitional zone's sustainable SES development coordination ability.

A grazing prohibition policy is a strategic measure that can solve desertification problems in northern China's farming-pastoral zones and help coordinate both the internal elements of the SES and the distribution of benefits among relevant subjects. The results are based on household behavior showing that desertification reversal and ecological rehabilitation are unsustainable in China without continued governmental intervention [43]. Once the grazing prohibition was enforced, the sustainability index of the SES shifted from "unsustainable" before grazing to "basic sustainable" in 2013 [44], and the coordination ability between the systems simultaneously shifted from "weak coordination" in the early stage to "high coordination" in the present stage. During the different stages of grazing prohibition, coordination ability variation was closely related to the execution of grazing policy; coordination ability declined rapidly, falling as low as the "weak coordination" level because the grazing prohibition dilemma occurred during the middle stage. Lu Huiling et al. (2015) [45] used the 'Technique for Order of Preference by Similarity to the Ideal Solution' (TOPSIS) method and an obstacles model to find that variation in the household income level, stealing, farmers' awareness of the environment's importance and an accepting attitude of ecological policy constitute the main obstacles to this ecological policy's sustainability. In summary, an ecological policy should be designed and implemented not only to protect farmers' livelihood (as the first consideration), but also to guarantee its sustainability. Only in this way can we resolve the contradiction between ecological policy and household income to effectively promote coordination between SESs. Because of the implementation of the "grassland ecology compensation award policy", SES coordination ability quickly entered the "high coordination" category, confirming that a system's diversity can effectively counteract the shortcomings of a single ecological policy via top-level design and grass-roots implementation to better promote coordination and sustainable development among SESs.

5.3. Deficiencies and Prospects of the Study

Our study has the limitations of a finite period and space. Indeed, the coordination ability of sustainable SES development was evaluated only after Yanchi County implemented the grazing prohibition policy. In fact, SES is a complex system that interacts with the dimensions of time, space, structure, material flow, energy and information. In the future, SESs should be considered from the perspectives of social-geography relationships, resources and element flows in space to analyze the system in its entirety and investigate relationships between the SES networks on a larger geographical scale. Second, with respect to the time scale, we did not consider the variation of SES coordination ability before grazing prohibition. Thus, we could not contrast the variation in the SES coordination ability before and after the grazing prohibition. Third, we ignored the ecological service indicators when we designed the evaluation index system in the beginning; this has the representative and typical feature of measuring the change in the ecological environment. Therefore, we should consider ecosystem services in our future research.

Although the time interval of this study was only twelve years, the coordination ability index showed an "M" trend every five years, which has occurred twice since the grazing prohibition policy was implemented in Yanchi County. As a result, questions remain: Will the observed trends exist on a longer time scale? Were the observed trends only attributable to the implementation of grazing prohibition? Can similar trends be identified in other typical areas of desertification reversal in pastoral transitional zones?

6. Conclusions

China has suffered from desertification for many years [46]. Combating desertification is a difficult task and involves complex systems engineering. One solution is to realize the internal coordinated development of SESs. Because of the heterogeneity of natural and socioeconomic environments, conducting an in-depth analysis of the ecological and socioeconomic environments of typical regions is necessary. This analysis will provide references and lessons for controlling desertification to formulate an ecological policy by exploring the variation in the coordination ability and the factors that influence the desertification reversal process.

Our analysis provides a comprehensive assessment of the long-term sustainability and SES coordination in a typical desertification reversal area using a growth curve function based on the SPA method. As a result of this analysis, the following conclusions can be drawn: (1) Yanchi County was typically in the second grade of the national sustainable development level, and the development trends of the subsystems became relatively stable, shifting from "weak identical potential" to "strong identical potential"; (2) sustainable coordination ability increased from 0.686 in 2003 to 0.957 in 2014 and from weak coordination to basic coordination to high coordination; (3) drought, the grazing prohibition dilemma and the ecological footprint were key factors in Yanchi County's SES coordination ability.

The study results indicated that the improvement of the ecological environment prompted desertification reversal and sustainable development. First, Yanchi County should abide by natural ecological laws, establish a grassland ecosystem-based ecological restoration plan and use a protective strategy to achieve the coordinated development of the SES and agriculture-livestock production. Second, the ecological protection policy should be based on ecological restoration with farmers as the first consideration by establishing appropriate ecological compensation and protection mechanisms for farmers to fully resolve the contradictions between the long-term ecological benefits of the ecological policy and short-term economic benefits for farmers. The value of system diversity should be recognized, and a relevant policy that conforms to the leading regional ecological policy should be introduced. Third, the development of economic and social systems should be improved to promote the population urbanization and tertiary industrial development. Considering the dual needs of local resource endowments and farmers' income growth, we should develop a new livestock system that addresses the dual constraints of the market and resources to reasonably guide farmers' production behavior and consumption structure, reducing the regional ecological footprint and stimulating coordinated and sustainable development between SESs.

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Abbreviations

The following abbreviations are used in this manuscript:

SES	Social-Ecological System
IDC	Identical-Discrepancy-Contrary
SPA	Set Pair Analysis
SPP	Set Pair Potential
CAI	Coordination Ability Index

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